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SUBJECT: Shuttle Launch Azimuth and On-Orbit Operations Time Constraints for Launch and Rapid Recovery at KSC
Case - 105-4

DATE: September 17, 1970

FROM: E. M. Grenning

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ABSTRACT

An economical mode of space shuttle operation is rapid recovery of the shuttle at its launch site. This is also attractive since it provides a very desirable abort capability. To accomplish this it is necessary to "aim" the shuttle at launch, such that a recovery at the launch site is possible using cross-range maneuvering at the end of any one of the first few orbits. This operational mode gives rise to both launch azimuth and on orbit operations time constraints. In this memorandum the constraints are determined for the case of shuttle launch from KSC followed by aerodynamic recovery immediately after any one of the first three orbits.

The resulting azimuth constraints for shuttles with Apollo class L/D ratios is generally the reduction of the region of available launch azimuths below that permitted by existing range safety restrictions. As the vehicle L/D, and hence its cross range capability, increases the range of permissible launch azimuths becomes larger. At certain threshold values of L/D, launch at any azimuth followed by rapid recovery becomes possible if range safety restrictions can be eliminated. Propulsive plane change maneuvering as a means of achieving cross range capability is not considered. The on-orbit operations time available depends primarily on the number of orbits executed prior to the deorbit maneuver and secondarily on the shuttle L/D ratio.

Based on the constraint data generated, several specific conclusions can be established. A minimum shuttle L/D of 1.6 provides one northerly in plane launch opportunity per day for logistics missions to a 55° inclination space station. For this mission, the maximum on orbit operations time corresponding to recovery immediately after the third orbit is 4.2 hours. Furthermore, all azimuth launch capability for a once around and recovery Air Force reconnaissance mission is also provided. For this mission, the total elapsed time from launch to recovery is 1.9 hours. The total elapsed time for once around and recovery in an abort situation varies from 1.7 hours for Apollo class L/D's to 1.9 hours for an L/D of 1.6, which corresponds to the all azimuth launch capability case.

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MEMORANDUM FOR FILE

I. Introduction

The most economical mode of space shuttle operation is to have both launch and recovery take place at a single site, preferably KSC because of the NASA's existing large investment in real estate and physical plant at that location. This mode achieves the majority of its economy by eliminating the need for a surface logistic or air ferry system to return the recovered orbital portion of the space shuttle to the launch site.

For heavy annual shuttle traffic, further economy can be obtained by rapid shuttle recovery since that would tend to reduce the vehicle inventory necessary to satisfy the program logistics requirements. The rapid recovery mode suggests a shuttle mission profile consisting of boost of the orbital portion of the shuttle and its payload to low earth orbit; separation, or transfer of the payload from the shuttle to another vehicle followed by return to KSC immediately after any one of the first several orbits. Profiles of this type are generally associated with propellant supply and space station logistics support operations, References 1 and 2.

Shuttle abort is another important reason for providing rapid recovery capability at KSC. Almost without exception the currently identified modes for space shuttle abort during ascent call for either a direct suborbital return to KSC or abort to orbit followed by once around and recovery at KSC, Reference 3. Another mission mode reportedly of interest to the Air Force consists of once around, and recovery at the launch site, with all azimuth launch capability.

To provide rapid recovery, the shuttle must be "aimed," at launch, in a direction such that after any one of the first several orbits KSC will lie within the shuttle's aerodynamic cross range capability.* This gives rise to launch azimuth constraints which if violated would preclude rapid recovery at KSC. Furthermore, the number of orbits executed prior to the shuttle deorbit maneuver constrains the available on-orbit operations

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* Propulsive plane change maneuvering as a means of achieving cross range capability is not considered.

time for cargo, propellant and/or crew transfer. This time constraint is also effected, to a lesser extent, by the shuttle L/D ratio.

In the following section the equations necessary for the determination of the launch azimuth and orbital time constraints as a function of cross range capability are developed. The azimuth constraints for recovery immediately after the first, second or third orbits are superimposed and combined with existing KSC launch azimuth range safety restrictions. The result is a set of three launch azimuth constraint envelopes corresponding to: (1) recovery at KSC immediately after the first orbit, (2) recovery at KSC immediately after the first or second orbits, and (3) recovery at KSC immediately after the first, second or third orbits. The orbital operations time constraints are expressed as a function of shuttle L/D ratio for one, two or three orbits.

II. Launch and Recovery Analysis

The analysis is based on the following assumptions:

1. The earth is spherical and rotates about its polar axis with an angular velocity of 15°/hr.

2. At any location on the earth's surface a 1 degree segment of a great circle is 60 nm in length.

3. There is no yaw steering or plane change maneuvering by the shuttle during ascent or orbital flight, respectively.

4. Regression of the ascending orbital node is negligible.

Figure 1 illustrates the earth in an inertially fixed frame of reference including the locations of the launch site at both shuttle launch and recovery. The shuttle is launched from KSC using an azimuth (α) that guarantees KSC to lie in the orbital plane at recovery T hours after launch.

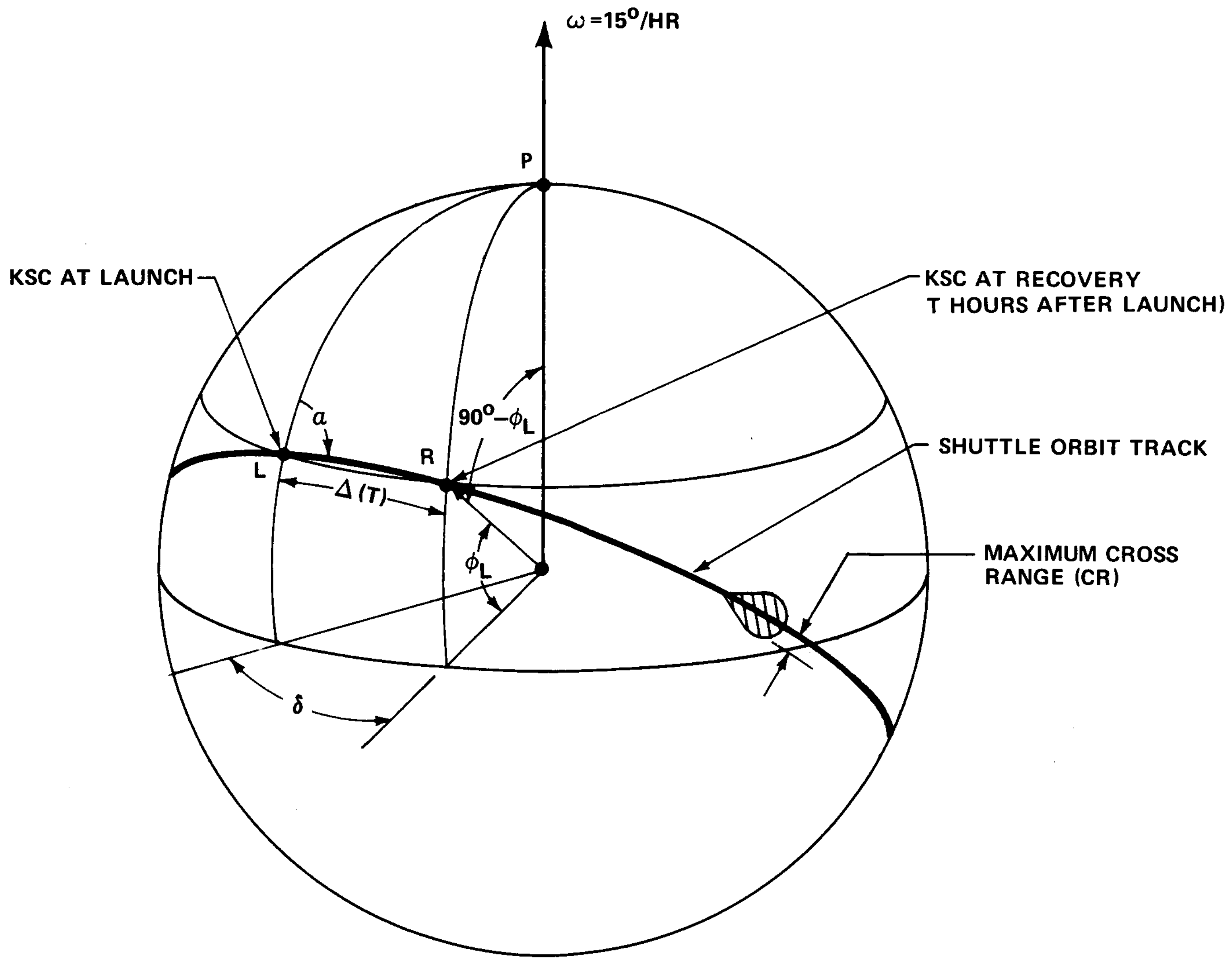

FIGURE 1 - LAUNCH AND RECOVERY GEOMETRY

The expression for cos α obtained by applying the law of cosines to the spherical triangle PLR in Figure 1. is

$$\cos\alpha = \tan \phi_L \left[\frac{1}{\sin\Delta(T)} - \frac{1}{\tan\Delta(T)} \right] \tag{1}$$

where:

α = launch azimuth necessary for KSC to lie in the orbital plane at recovery (deg.),

ϕ_L = latitude of launch site (for KSC, $\phi_L = 28.5°$),

$\Delta(T)$ = segment of orbit track between KSC at launch and recovery (deg.).

To determine the launch azimuth (α) from equation (1) it is first necessary to evaluate the orbit track segment $\Delta(T)$. The following expression for cos Δ (T) is obtained by again applying the law of cosines to the spherical triangle PLR.

$$\cos\Delta\ (T) = \sin^2\phi_L + \cos\delta\ \cos^2\phi_L \tag{2}$$

where:

δ = 15T (15°/hr, the earth rotational speed)

T = time elapsed from shuttle launch to recovery (hrs.)

As illustrated in Figure 2. the time elapsed from shuttle launch to recovery is composed of three parts,

$$T = t_a + t_o + t_d \tag{3}$$

where:

t_a = time elapsed from shuttle lift off to orbital insertion,

t_o = time elapsed from shuttle insertion to deorbit,

t_d = time elapsed from shuttle deorbit to touchdown.

Because of the absence of firm shuttle ascent trajectory data, the time elapsed (t_a) and central angle traversed (θ_a) from lift off to insertion were assumed constant and equal to typical values for a Saturn V launch, i.e., t_a = .188 hours and θ_a = 28.4°, Reference 4.

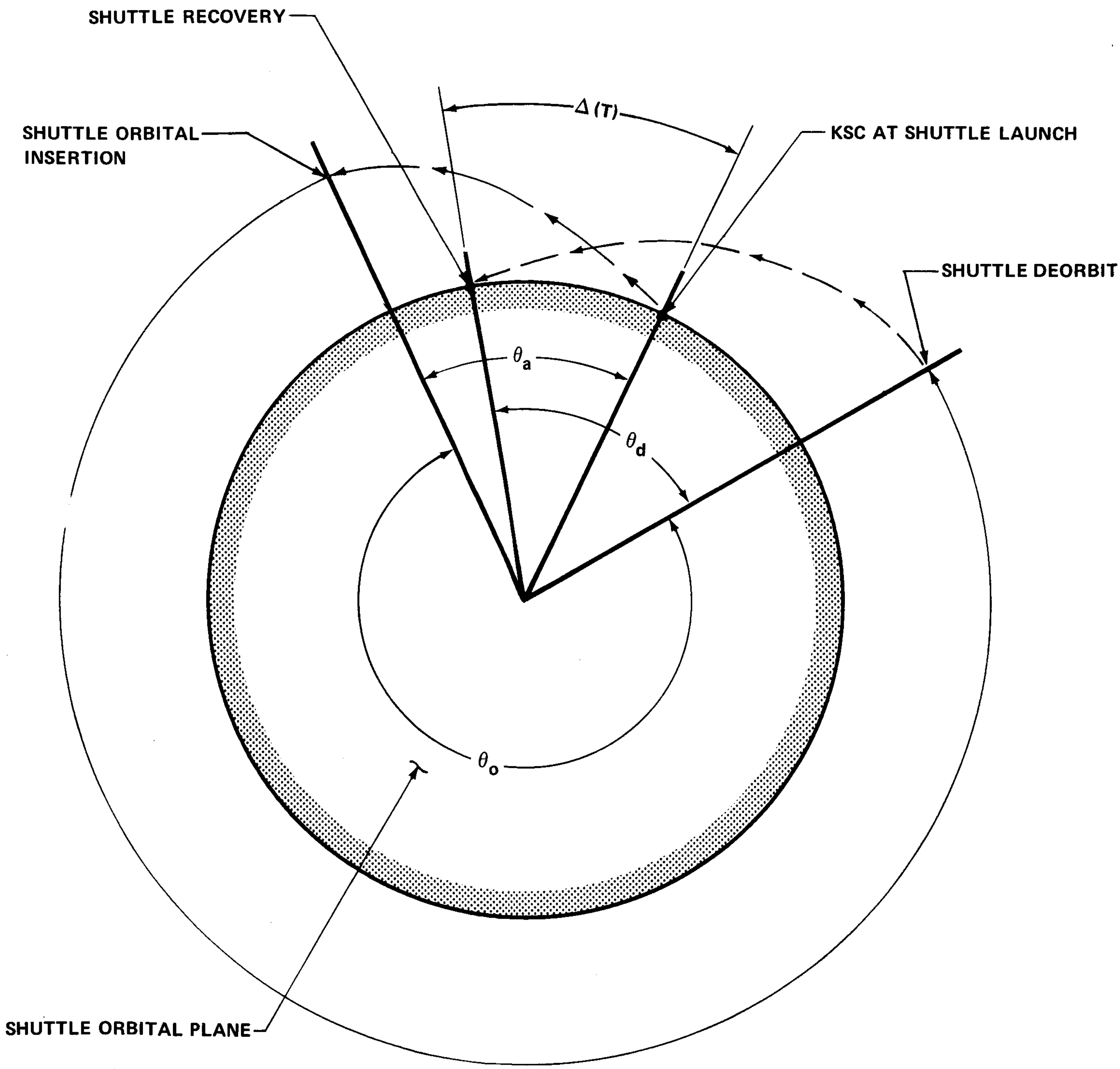

FIGURE 2 - SHUTTLE ORBITAL PLANE ANGULAR CONSIDERATIONS

The time (t_d) and traversed downrange central angle (θ_d) from shuttle deorbit to touchdown are primarily a function of the maximum hypersonic L/D ratio. Data from references 5 and 6 given in Table 1, show that descent time and downrange central angle increase as L/D becomes larger.

The time elapsed (t_o) and central angle traversed (θ_o) during orbital flight is a function of the angular location of the deorbit point. However, for a given θ_d the location of the deorbit point depends on the angular location of KSC (Δ) at shuttle touchdown, which in turn depends on the elapsed time (T) from lift off to touchdown. Since T depends partially on the amount of time spent in orbital flight (t_o), an iteration scheme must be used to determine the correct value of t_o and therefore T. From Figure 2 it is clear that the following equality must be satisfied for the shuttle to land at KSC T hours after launch.

$$\theta_a + \omega_o t_o + \theta_d = n(360) + \Delta(T) \tag{4}$$

where:

θ_a = 28.4° = central angle traversed during ascent,

ω_o = shuttle orbital angular velocity (deg/hr),

θ_d = downrange central angle traversed during descent (deg.),

n = integral number of shuttle circuits of earth as measured from position of KSC at shuttle launch (deg.),

$\Delta(T)$ = angular movement of KSC in the orbit plane, from shuttle launch to recovery.

Equations 1) through 4) are solved iteratively for α for parametric values of n.

The launch azimuth defined by the previous analysis (α) will bring the shuttle back on an orbit directly over the launch site. If the shuttle has cross range capability, however, the return orbit does not have to pass directly over the launch site, but can miss it by the amount of the maximum cross range capability.

TABLE 1. DEORBIT TO TOUCHDOWN-TIME AND DOWNRANGE CENTRAL ANGLE VS. MAXIMUM HYPERSONIC L/D

L/D	θ_d (deg.)	t_d (hrs.)
.25	49.3	.259
1.00	72.1	.430
1.50	91.8	.592
2.00	112.5	.747
2.50	135.0	.916
3.00	159.8	1.090

Note: The difference between downrange central angle and total angle traversed including the cross range effect is negligible. Maximum deceleration for all entry trajectories is less than 3g's.

As shown in Figure 3 the effect is to produce a domain of possible launch azimuths whose median value is the launch azimuth α. Clearly, as cross range capability increases the extent of the permissible launch azimuth domain also increases. One half of the symmetrical domain (α') is determined by applying the law of sines to the right spherical triangle (CLR), i.e.

$$\sin\alpha' = \frac{\sin(CR)}{\sin\Delta(T)} \tag{6}$$

where:

α' = one half of domain of permissible launch azimuths (deg.)

CR = shuttle maximum cross range capability expressed in terms of central angle (deg).

Equation (6) is solved for α' using the value of Δ (T) obtained from the above iterative procedure and cross range capabilities of from 100nm to about 5,000nm. The northerly launch azimuth constraint is then given by:

$$\Sigma_N = \alpha - \alpha' \tag{7}$$

and the southerly constraint by:

$$\Sigma_S = \alpha + \alpha' \tag{8}$$

The relationship between maximum hypersonic L/D and shuttle cross range capability is presented in Figure 4, from references 7 and 8. For a vehicle with a given L/D this relationship provides its corresponding maximum cross range capability as determined by aerodynamics only. If a more constraining influence, e.g., a thermal limitation, dictates entry flight at a lower L/D ratio, the vehicle maximum cross range capability would be correspondingly lower. Figure 4 allows determination of the maximum hypersonic L/D corresponding to any set of launch azimuth constraints. The results of the analysis as represented by equations (1) through (8) are presented and discussed in the following section.

III. RESULTS

Figure 5 presents both the median launch azimuth (α) and the range of permissible launch azimuths ($2\alpha'$) as a function of orbital altitude. The permissible launch azimuth domain is

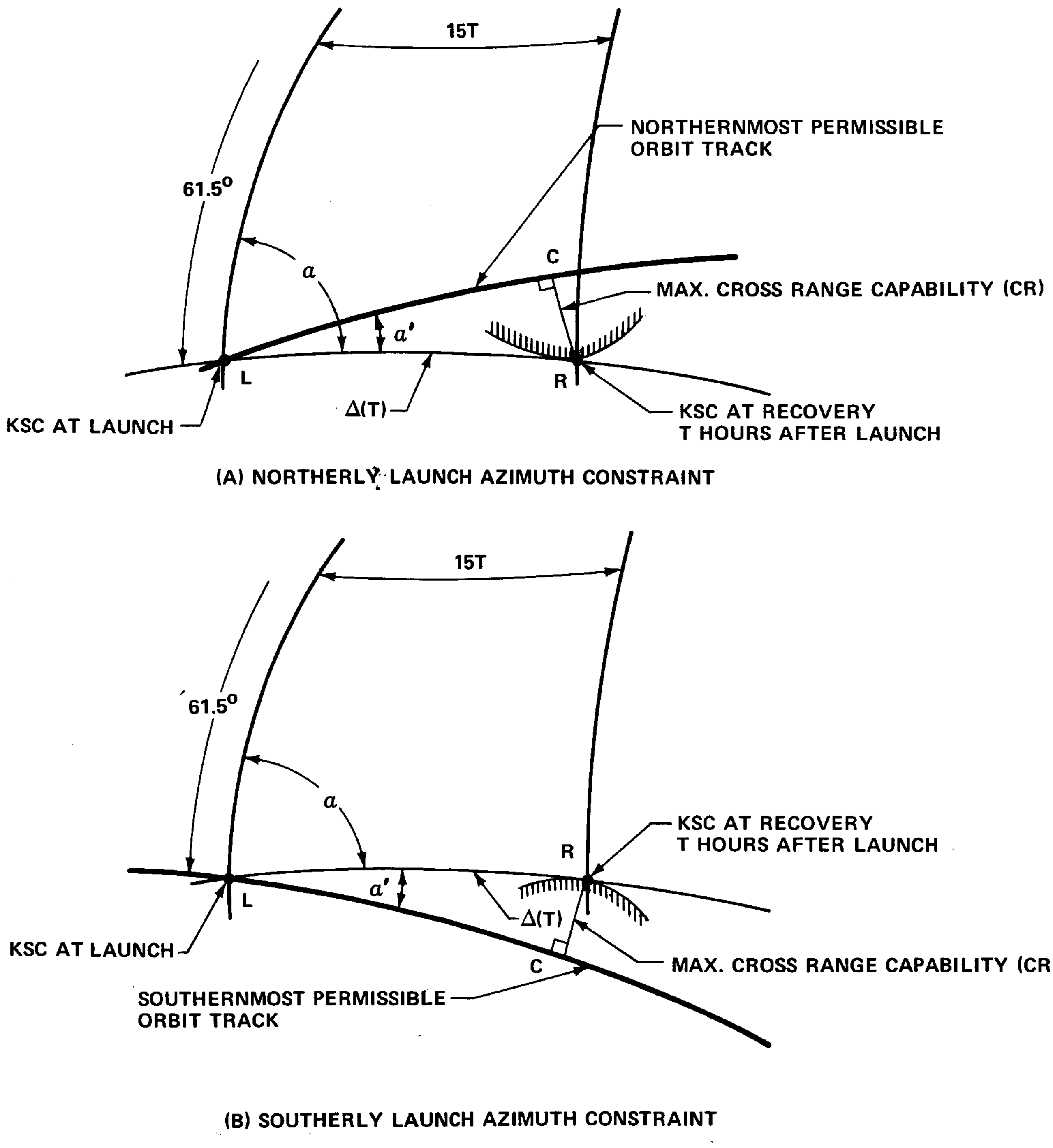

FIGURE 3 - EFFECTS OF SHUTTLE CROSS RANGE CAPABILITY ON NORTHERY AND SOUTHERLY LAUNCH AZIMUTH CONSTRAINTS

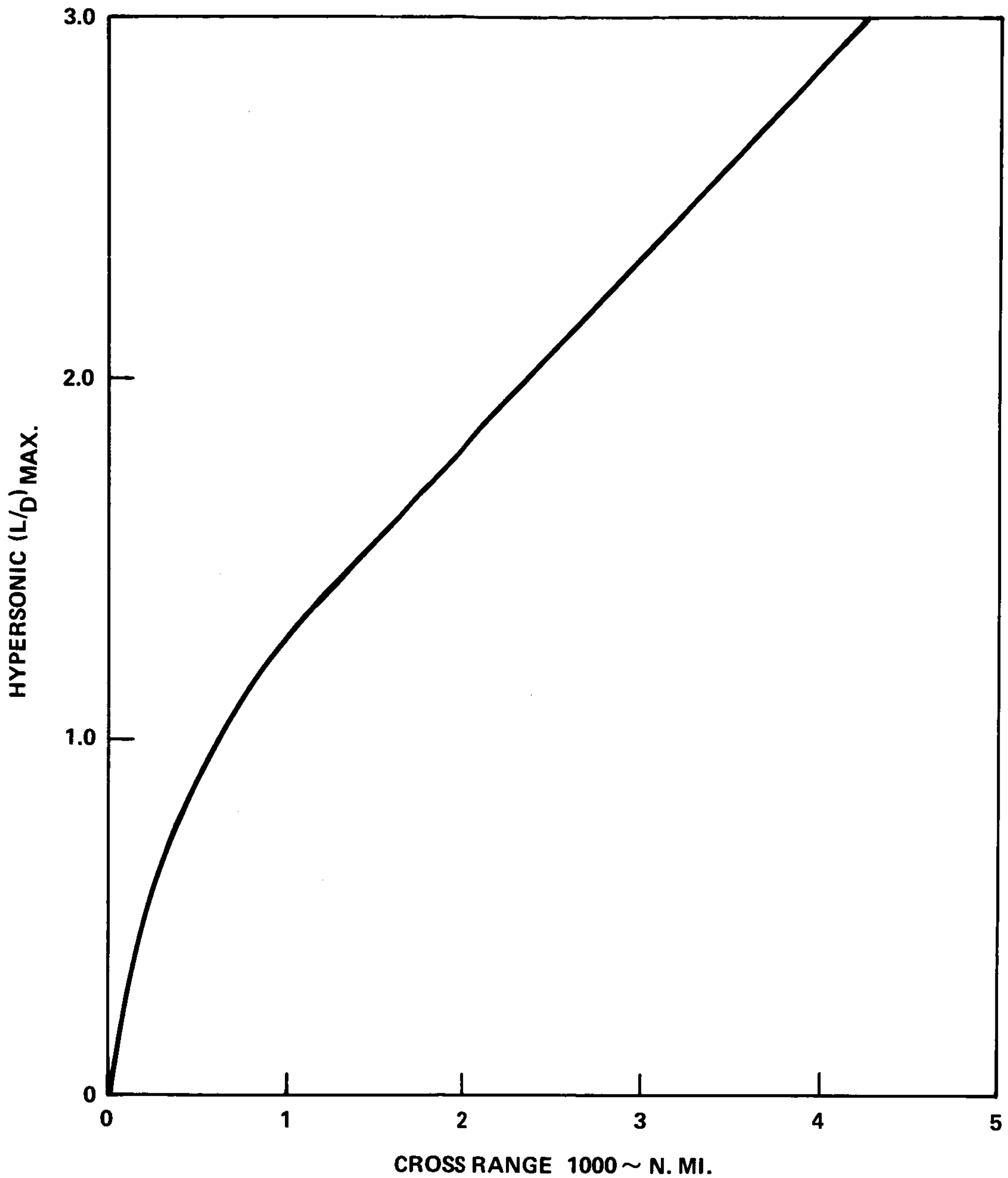

FIGURE 4 - CROSS RANGE CAPABILITY (NM) VS. HYPERSONIC $(L/D)_{MAX}$.

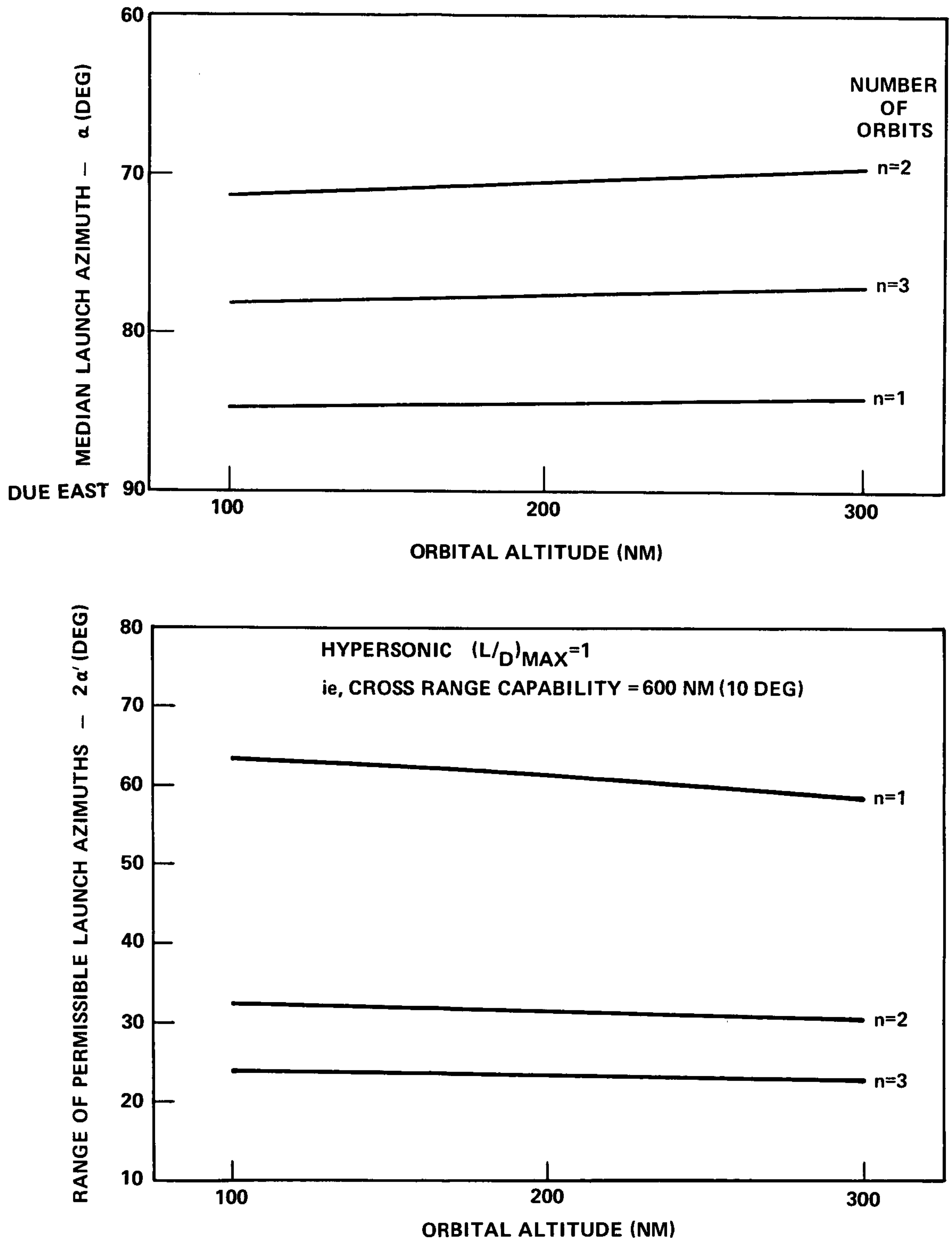

FIGURE 5 - SENSITIVITY OF α AND α′ TO CIRCULAR ORBITAL ALTITUDE

for a cross range capability of 600 nm which corresponds to a maximum L/D of 1. The influence of different orbital altitudes is generated by different values of orbital angular velocity in equations 4 and 5. From the figure it is clear that for orbital altitudes between 100 and 300 nm there is negligible variation in α and α'.

Northerly (Σ_N) and southerly (Σ_S) launch azimuth constraints for shuttle recovery immediately after the first, second or third orbit (n = 1, 2, and 3) are presented in Figure 6 as a function of cross range capability. The curves are valid for any altitude between 100 and 300 nm because altitude has such a weak influence. Orbital inclinations corresponding to the launch azimuths are indicated by the double ordinate scales.

The azimuth constraint curves of Figure 6 each represent shuttle recovery immediately after the n^{th} orbit (n = 1, 2, and 3) and not before, i.e., the n = 3 curve is for recovery immediately after the third orbit but not necessarily the first or second. To determine the azimuth constraints for shuttle recovery after any one of the first three orbits from launch the n = 1, 2, and 3 curves of Figure 6 were superimposed and the common domain of permissible launch azimuths determined for each value of cross range capability. The same procedure was used to determine the azimuth constraints for shuttle recovery within two orbits from launch except that only the n = 1 and n = 2 curves of Figure 6 were used. The azimuth constraints for once around recovery is merely the n = 1 curve of Figure 6, which for convenience, is reproduced in Figure 7. Figures 8 and 9 show resultant launch azimuth constraint curves for recovery within two and three orbits, respectively.

Also, indicated in Figures 7, 8, and 9 are the KSC range safety launch azimuth restrictions, a 55° space station orbital inclination and the launch azimuth that gives rise to an east coast overfly. The range safety restrictions arise from the prohibition of overflight of Bermuda to the north and Cuba to the south. Currently the restrictions are firm, any change requiring approval at the executive level of government. The 55° space station orbital inclination is that prescribed in the Phase B Space Station Definition Study Statement of Work, Reference 9. The inclination is based partially on a desire for the station to overfly as large a percentage of existing ground truth stations as is practicable. If space shuttle overflight of land during its ascent is prohibited, then the indicated east coast overflight launch azimuth would be a launch azimuth constraint, perhaps one of a new set of range safety constraints.

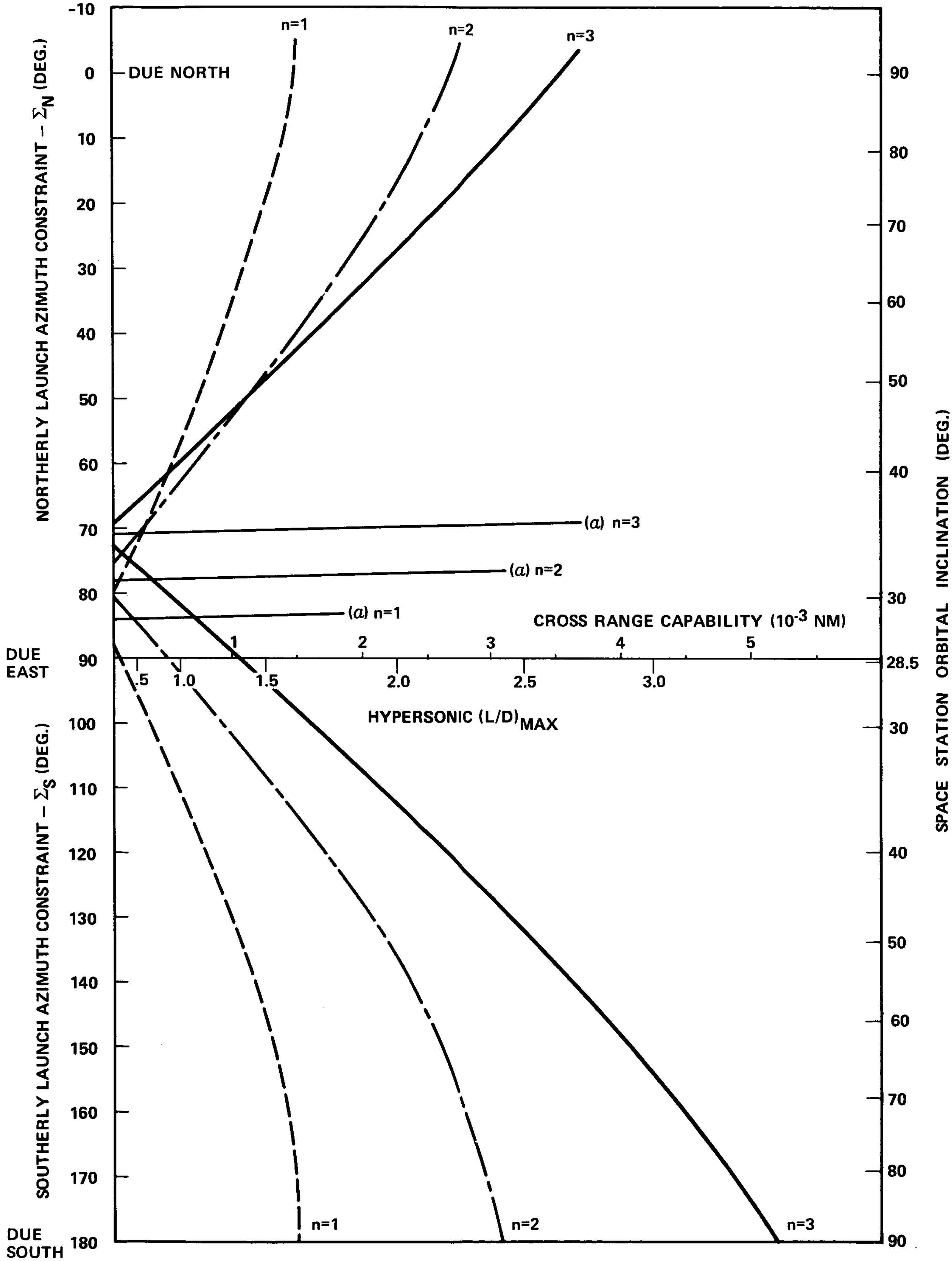

FIGURE 6 - KSC LAUNCH AZIMUTH CONSTRAINTS VS CROSS RANGE CAPABILITY

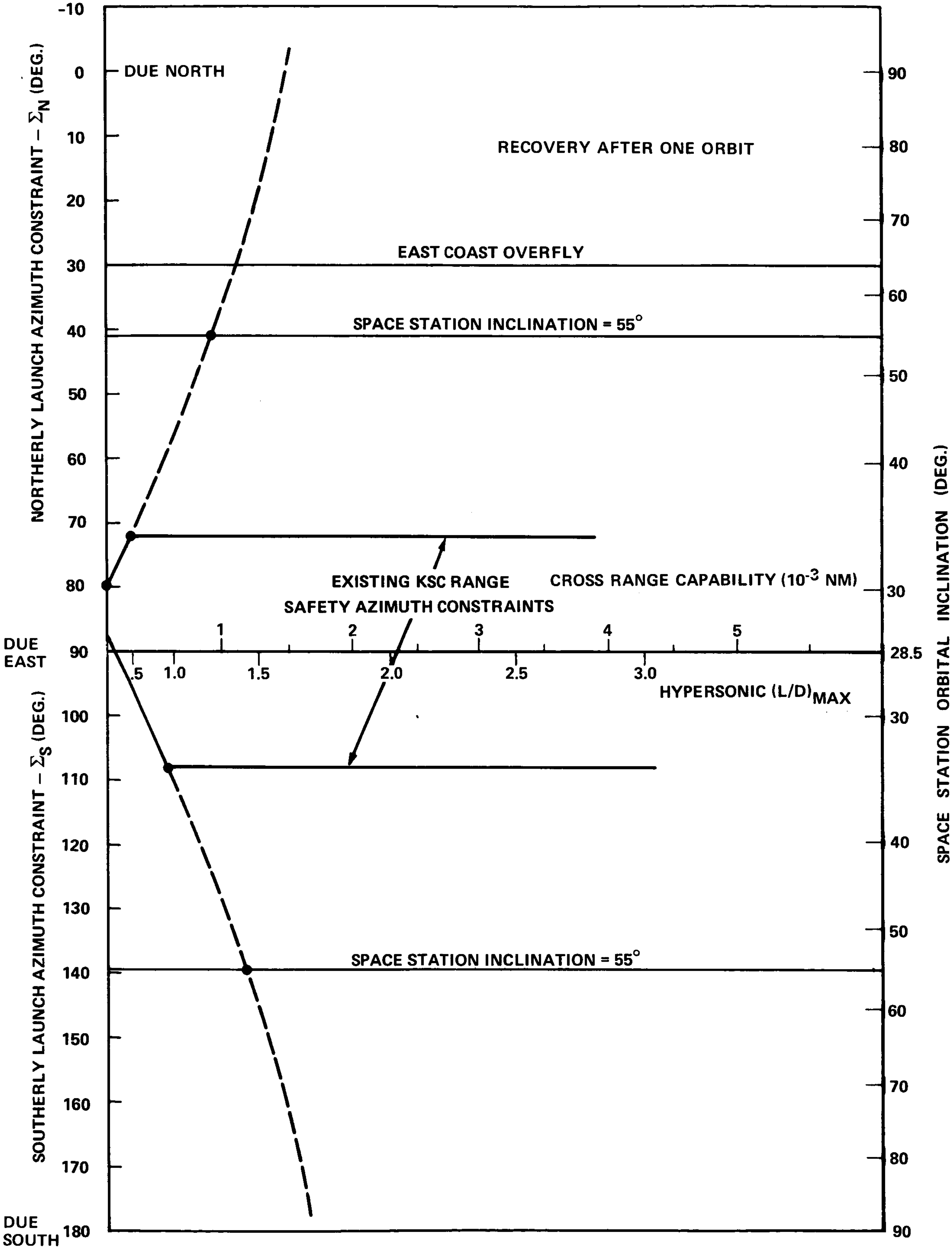

FIGURE 7 - KSC LAUNCH AZIMUTH CONSTRAINTS VS CROSS RANGE CAPABILITY

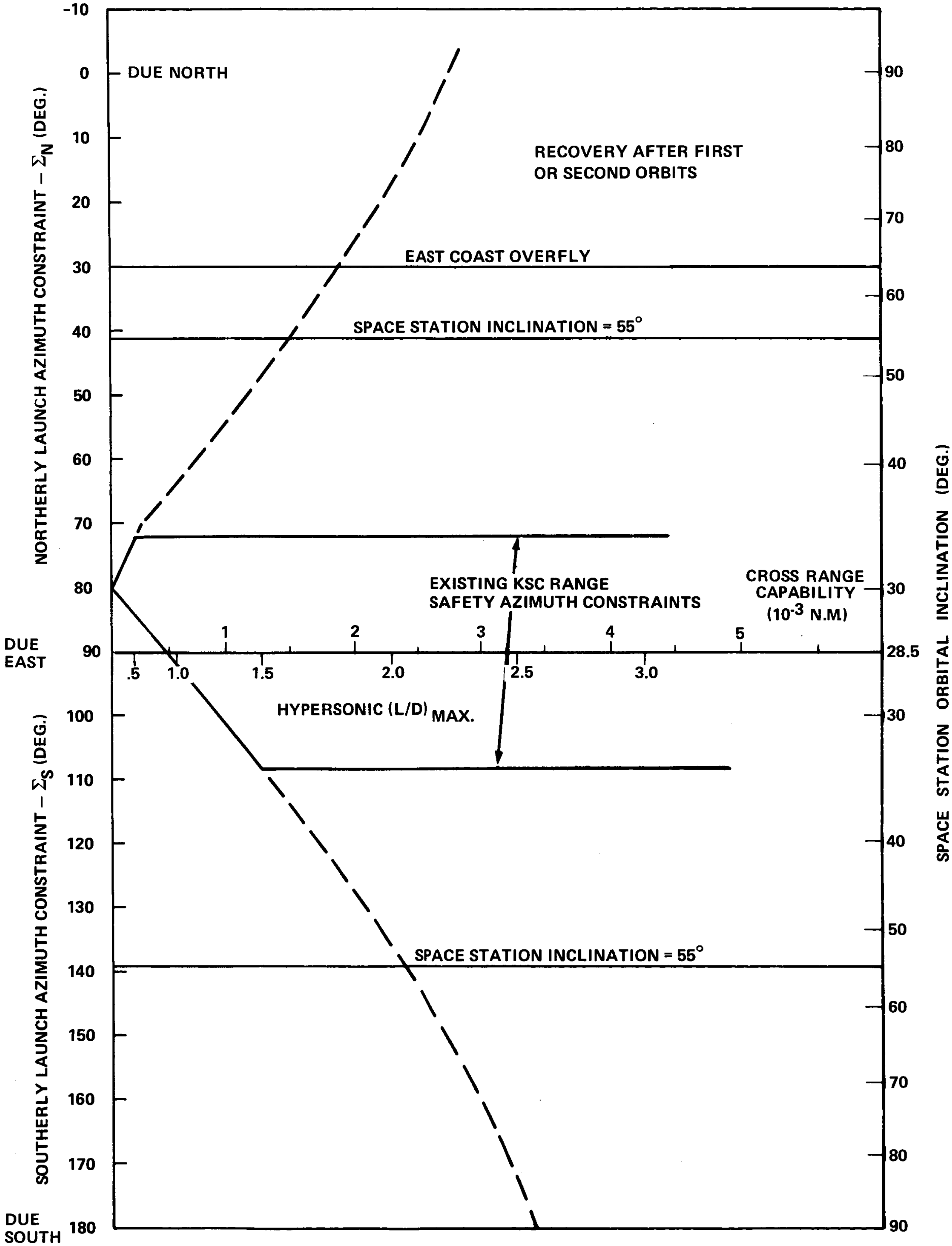

FIGURE 8 - KSC LAUNCH AZIMUTH CONSTRAINTS VS CROSS RANGE CAPABILITY

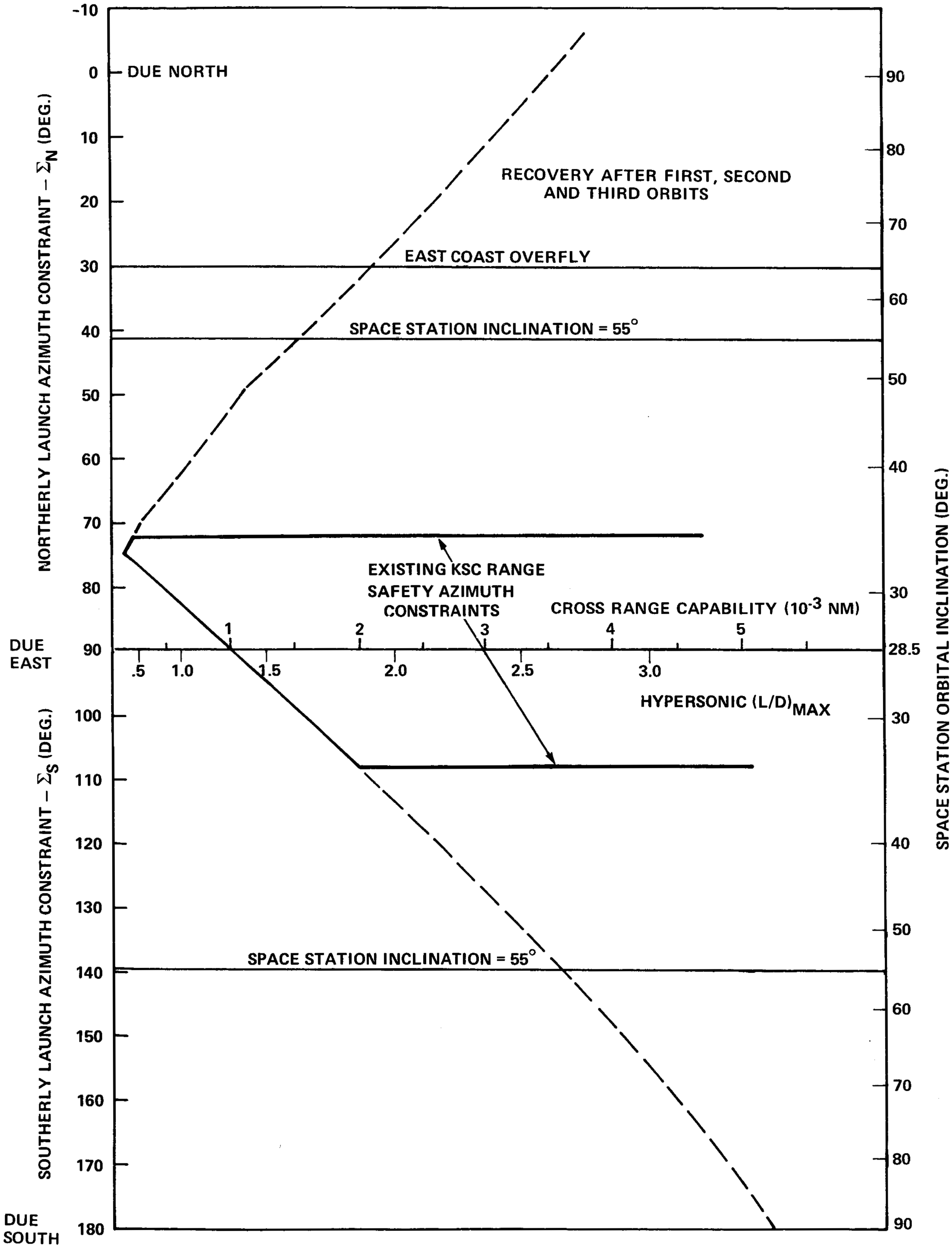

FIGURE 9 - KSC LAUNCH AZIMUTH CONSTRAINTS VS CROSS RANGE CAPABILITY (10^{-3} NM)

In Figures 7 through 9 as the L/D ratio increases from its lowest value on the scale (Apollo class) the region of permissible launch azimuths becomes larger. The northerly and southerly azimuth constraints first intersect the northern and southern range safety restrictions, respectively. Then, with further divergence the constraints intersect the space station inclination lines and the northern constraint crosses the east coast overfly line immediately thereafter. The constraints are terminated at a value of L/D which provides all azimuth launch capability. Table 2 presents the numerical data corresponding to the intersection points.

Using an iterative procedure, the on-orbit operations time constraints are obtained from equation 4, and are presented in Figure 10 as a function of L/D ratio for parametric values of n. The time in orbit constraint is primarily determined by the number of orbits executed between launch and recovery (n = 1, 2, and 3) and secondarily effected by the shuttle L/D ratio. For a given number of orbits, as L/D increases from an Apollo class value, the time in orbit constraint slowly decreases due to the increased descent cruise time required for higher L/D vehicles (see Table 1). Also shown in Figure 10 is the locus of threshold values of L/D beyond which all azimuth launch capability exists.

As the earth rotates, KSC will pass through the space station plane twice per day establishing two daily in-plane shuttle launch opportunities for space station logistics missions. As indicated in Figures 7 through 9 for a space station inclination of 55° one of the opportunities requires a 41° launch azimuth and the other an azimuth of 139°. Since both azimuths exceed current range safety restrictions the two daily in-plane opportunities exist only if the restrictions can be ignored or enlarged to include the required azimuths. If the existing restrictions must be observed, then, as indicated in Figures 7 through 9 the alternative mode of providing the two daily in-plane opportunities is to choose a space station inclination between 28.5° and 34°.

The relationship between minimum L/D for in-plane launch constrained by rapid shuttle recovery, and number of orbits after launch (n) has been determined from the data in Figures 7 through 9 and is presented in Figure 11. It was tacitly assumed that current range safety restrictions could be ignored. The two curves in Figure 11 represent the aforementioned relationship for; 1) two daily in-plane launch opportunities at an azimuth of 41° and 139°, and 2) one daily in-plane opportunity at an azimuth of 41°. If one daily in-plane opportunity is sufficient, it can be seen that a minimum shuttle L/D of 1.63 would provide rapid recovery after any one of the first three orbits while the

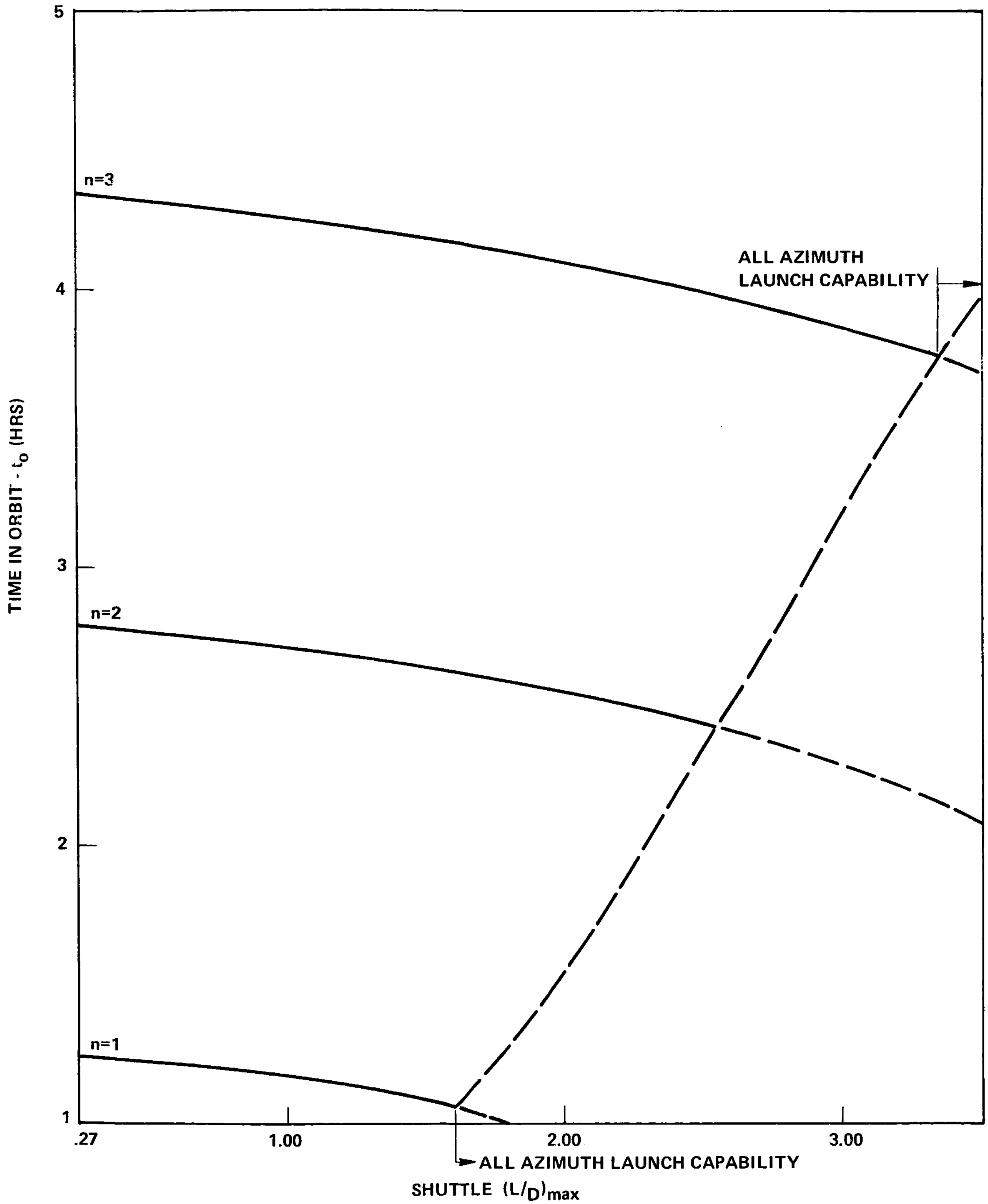

FIGURE 10 - AVAILABLE OPERATIONS TIME IN ORBIT VS SHUTTLE $(L/_D)_{max}$

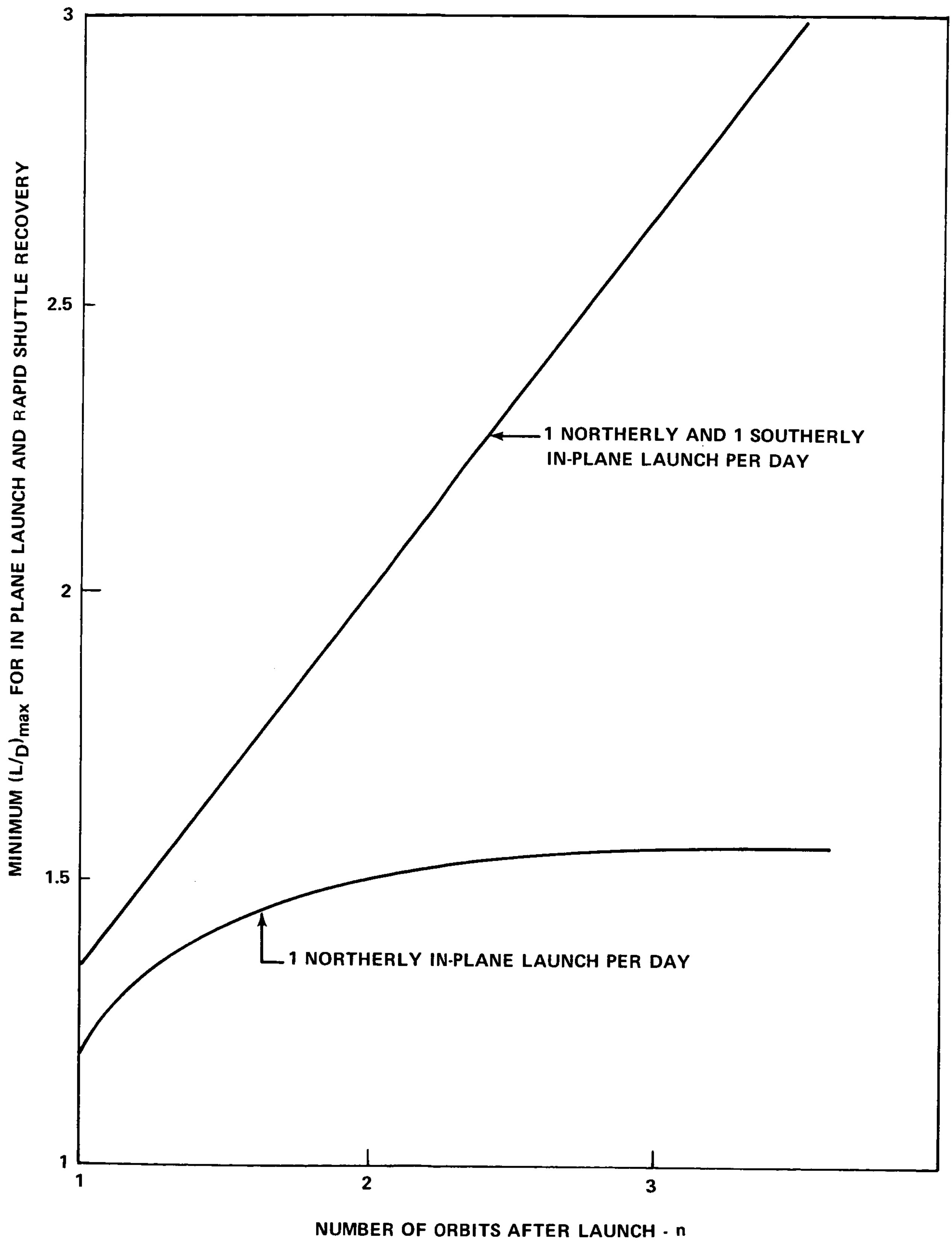

FIGURE 11 - MINIMUM $(L/D)_{max}$ FOR IN PLANE LAUNCH TO 55° INCLINATION SPACE STATION WITH RAPID RECOVERY CAPABILITY

same recovery capability for two in-plane opportunities per day requires a minimum L/D of about 2.7. Presuming one opportunity per day is acceptable for shuttle operations, Table 2 shows that an L/D of 1.63 would also provide all azimuth launch capability for the once around the recovery Air Force reconnaissance mission.

More generally, minimum L/D requirements for all azimuth launch capability corresponding to n = 1, 2, and 3 have been determined from Figures 7 through 9 and are given in Table 3. Also, included are the corresponding elapsed times from launch to recovery, e.g., the elapsed time for the Air Force reconnaissance mission is 1.9 hours. From Figure 10, the on-orbit times for space station logistics missions corresponding to shuttle L/D's of 1.63 and 2.7 are 4.2 hours and 4 hours, respectively. In the case of an abort during shuttle ascent, the elapsed time for the once around and recovery mode varies from 1.7 hours for Apollo class L/D's to 1.9 hours for an L/D of 1.63, which corresponds to the all azimuth launch capability case.

IV. Conclusions

In pursuit of an economical mode of space shuttle operation it is desirable to recover the shuttle at the same site from which it is launched thus eliminating the need for a surface air ferry system. Accomplishment of this objective gives rise to launch azimuth and on-orbit operations time constraints which have been determined herein for up to three orbits from launch.

The region of permissible launch azimuths for shuttles with Apollo class L/D's is smaller than that permitted by existing range safety restrictions. As the shuttle L/D ratio and hence its cross range capability increases the range of permissible launch azimuths also increases. At certain threshold values of L/D launch at any azimuth becomes possible if range safety restrictions can be eliminated.

The on-orbit operations time available depends primarily on the number of orbits (n = 1, 2, or 3) executed prior to the deorbit maneuver. A secondary influence is the shuttle L/D ratio because of its effect on the vehicle descent cruise time.

The following conclusions are consistent with shuttle recovery at KSC after any one of the first three orbits.

TABLE 2 - Launch Azimuth Constraints

Data Summary

n = 1 (Figure 7)	Apollo Class	Range Safety		S. S. Inclination		East Coast Overfly	All Azimuth Launch Capability
		North	South	North	South		
Σ_n (deg)	79.5	72	63	41	28.5	30	0
Σ_s (deg)	88.2	95	108	126	139	N/A	180
L/D	.27	.58	.90	1.25	1.40	1.37	1.60
CR (nm)	100	270	550	920	1200	1150	1500
n = 2 (Figure 8)							
Σ_n (deg)	79.9	72	47.5	41	17	30	0
Σ_s (deg)	80.5	85	108	115	139	N/A	180
L/D	.27	.58	1.42	1.60	2.03	1.80	2.55
CR (nm)	100	270	1250	1500	2350	1900	3400
n = 3 (Figure 9)							
Σ_n (deg)	75.5	72	32	41	-2	30	0
Σ_s (deg)	75.5	76.5	108	100	139	N/A	180
L/D	.50	.58	1.82	1.63	3600	1.90	3.50
CR (nm)	200	270	2000	1550	2.65	2100	5250

Table 3

All Azimuth Launch Capability - L/D
Requirements and Corresponding Elapsed Times

n =	1	2	3
L/D	1.6	2.5	3.3
T (hrs.)	1.9	3.5	5.4

1. A minimum shuttle L/D of 1.63 provides one northerly inplane launch opportunity per day (azimuth = 41°) for logistics missions to a 55° inclination space station.

2. For this mission the maximum on-orbit operations time corresponding to recovery immediately after the third orbit is 4.2 hours.

3. A shuttle L/D of 1.63 also provides all azimuth launch capability for a once around and recovery Air Force reconnaissance mission.

4. For the reconnaissance mission the elapsed time from lift-off to touchdown is 1.9 hours.

5. In an abort situation the elapsed time from lift-off to touchdown varies from 1.7 hours for Apollo class L/D's to 1.9 hours for an L/D of 1.63

The remaining two conclusions are concerned with the relationship between the shuttle and the space station orbital inclination.

6. If the shuttle L/D design objective is not achieved, reduction of the space station orbital inclination from 55° to a lower value can be used as a means of maintaining rapid recovery capability at KSC for shuttle logistics missions.

7. If existing range safety azimuth restrictions cannot be eliminated or changed; then to avoid the need for space shuttle yaw steering or plane change maneuvering the space station inclination should be between 28.5° and 34°.

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1012-EMG-pak E. M. Grenning

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